(12) UK Patent Application (19) GB (11) 2 046 955 A

(21) Application No 8005832
(22) Date of filing 21 Feb 1980
(30) Priority data
(31) 15713U
38667
(32) 27 Feb 1979
14 May 1979
(33) United States of America (US)
(43) Application published 19 Nov 1980
(51) INT CL³
G05D 3/12
G01P 3/36
G05D 3/20
(52) Domestic classification
G3R A273 A34 BC23
G1A A3 C12 C3 C8 C9 CE D10 G17 G18 G1 G7 G8 P12 P16 P1 P6 R7 S12 S13 S4 T14 T26 T3 T8 T9
G3N 275 277A E3X
(56) Documents cited
None
(58) Field of search
G3N
G3R

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(54) Interferometrically controlled stage with precisely orthogonal axes of motion

(57) A projection lens (26) is mounted between a movable stage and a stationary holder (28) to project an image of a reticle (14) held by the holder onto a semiconductive wafer (12) held by a chuck (22) mounted on the stage. The stage is movable along orthogonal X and Y axes in a horizontal plane to align different regions of the semiconductive wafer with the projected image of the reticle. First and second movable plane mirrors (30, 32) fixedly mounted on the stage for movement therewith are symmetrically disposed relative to the Y axis in first and second vertical planes intersecting one another at the Y axis. Similarly, first and second stationary plane mirrors (36, 38) fixedly mounted on a housing of the projection lens are disposed parallel to the first and second movable mirrors, respectively. As the stage is moved along the X and Y axes, first and second interferometer systems (40, 42) provide first and second measurement signals indicative of the velocities of the first and second movable mirrors (relative to the first and second stationary mirrors) while they are being moved along first and second measurement paths normal to the first and second movable mirrors, respectively. In response to the sum and the difference of these measurement signals, first and second position control circuits move the stage along precisely orthogonal X and Y axes with the Y axis bisecting the angle between the first and second movable mirrors until a predetermined position is reached.

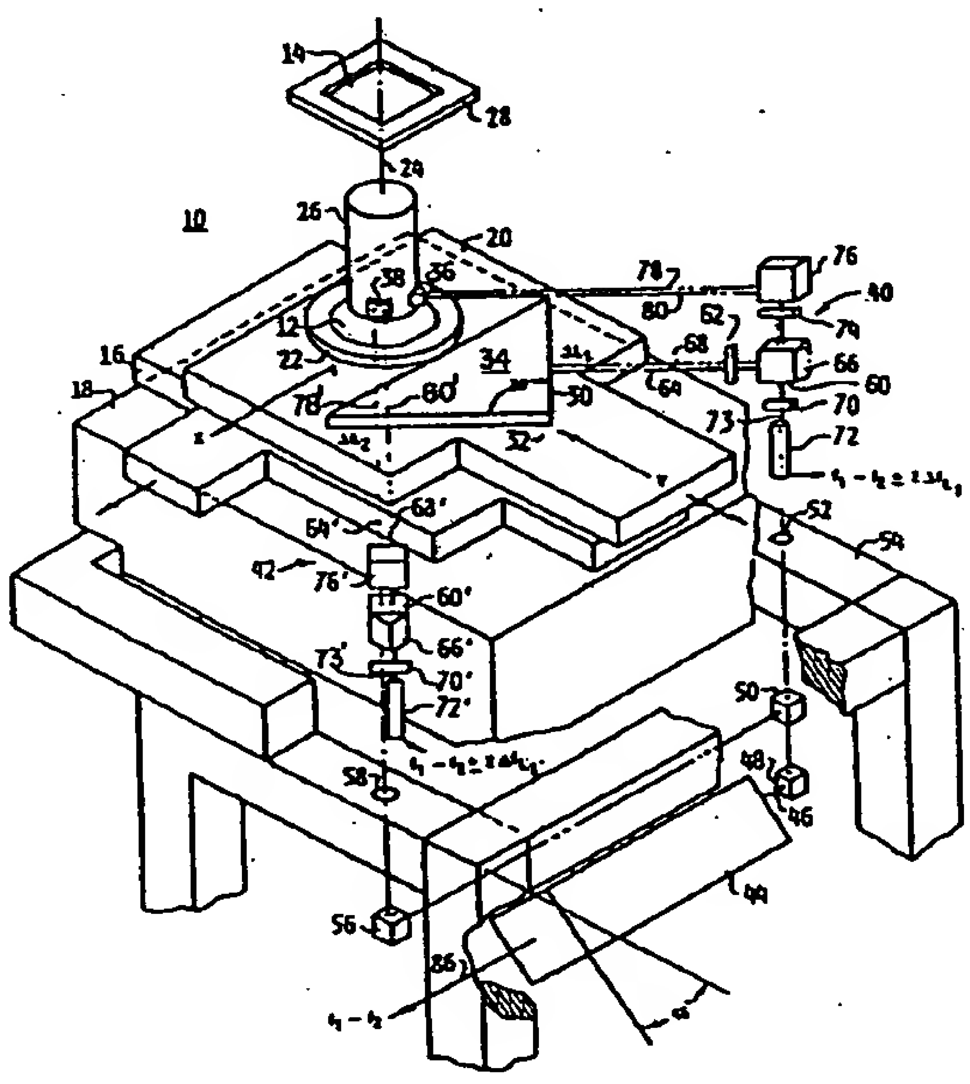

FIG 1

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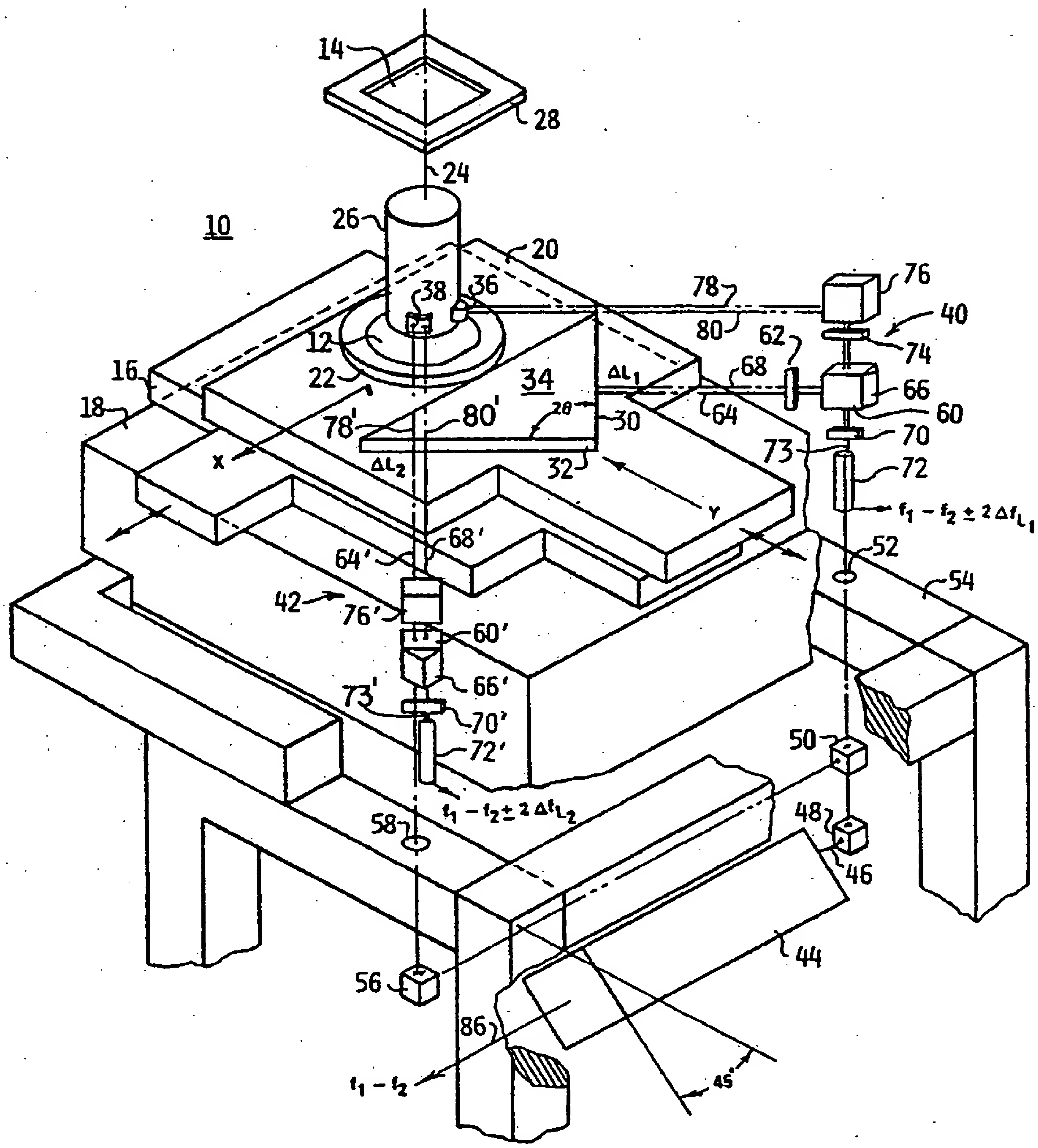

FIG 1

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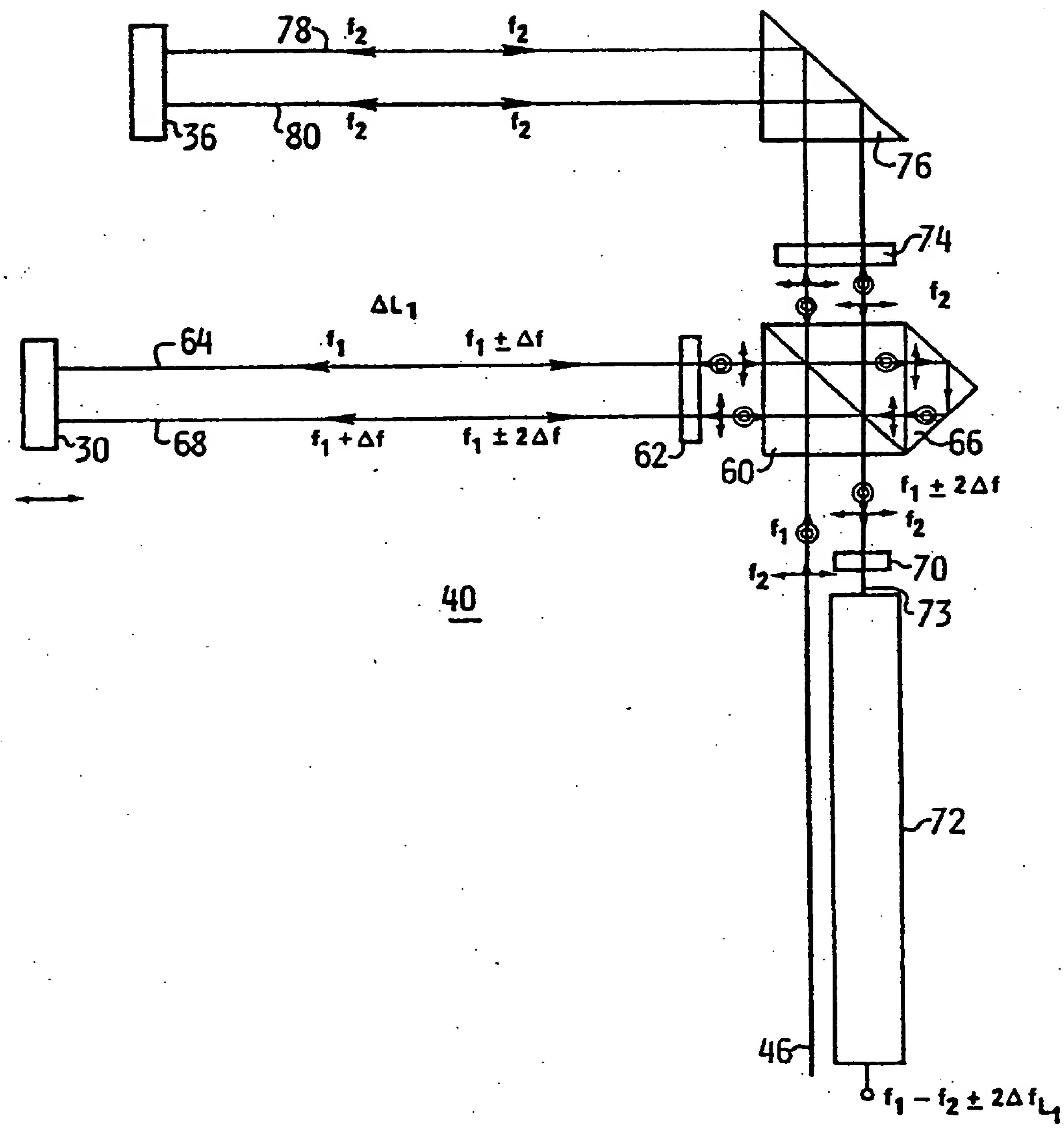

FIG 2

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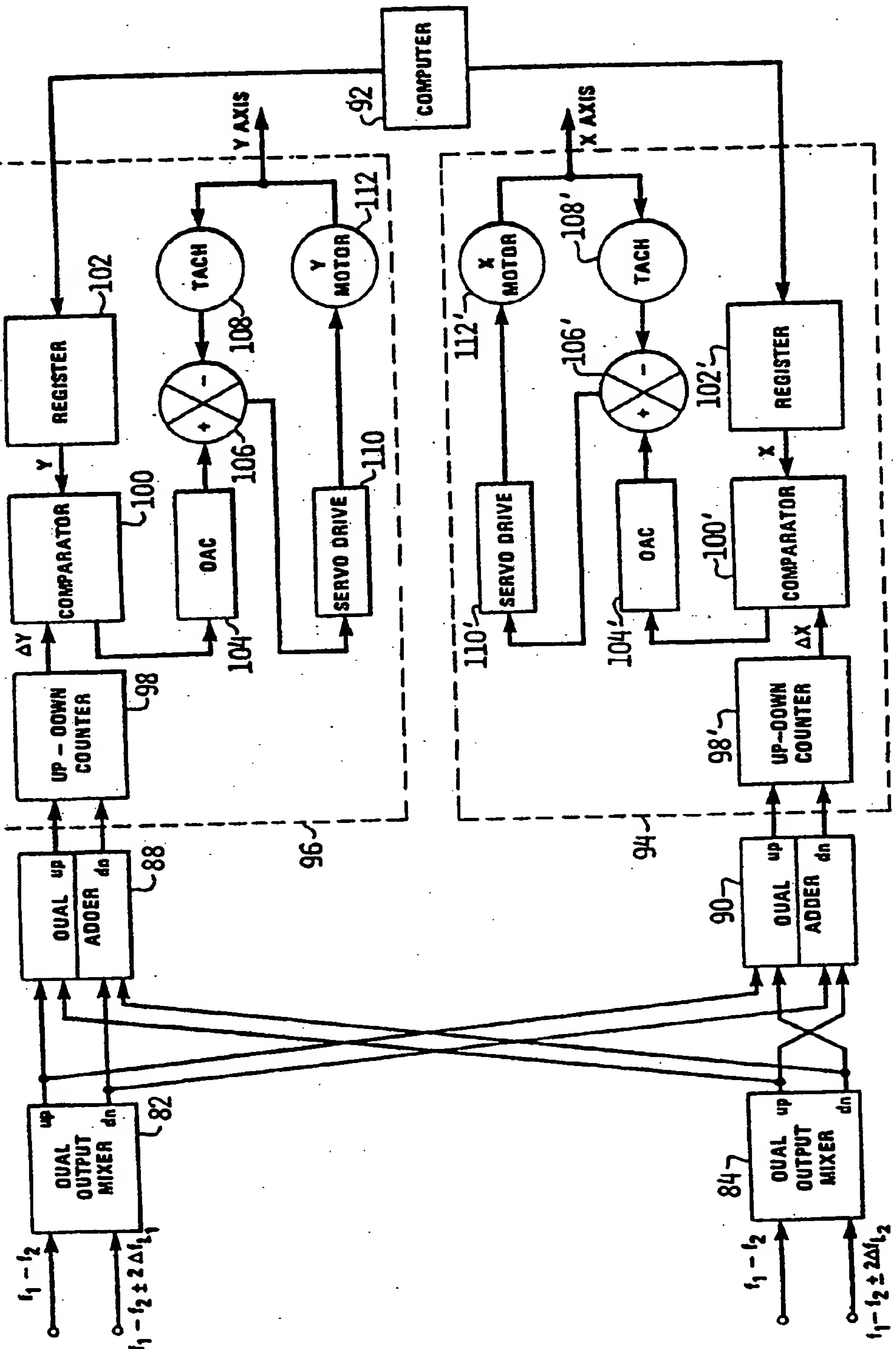

FIG 3

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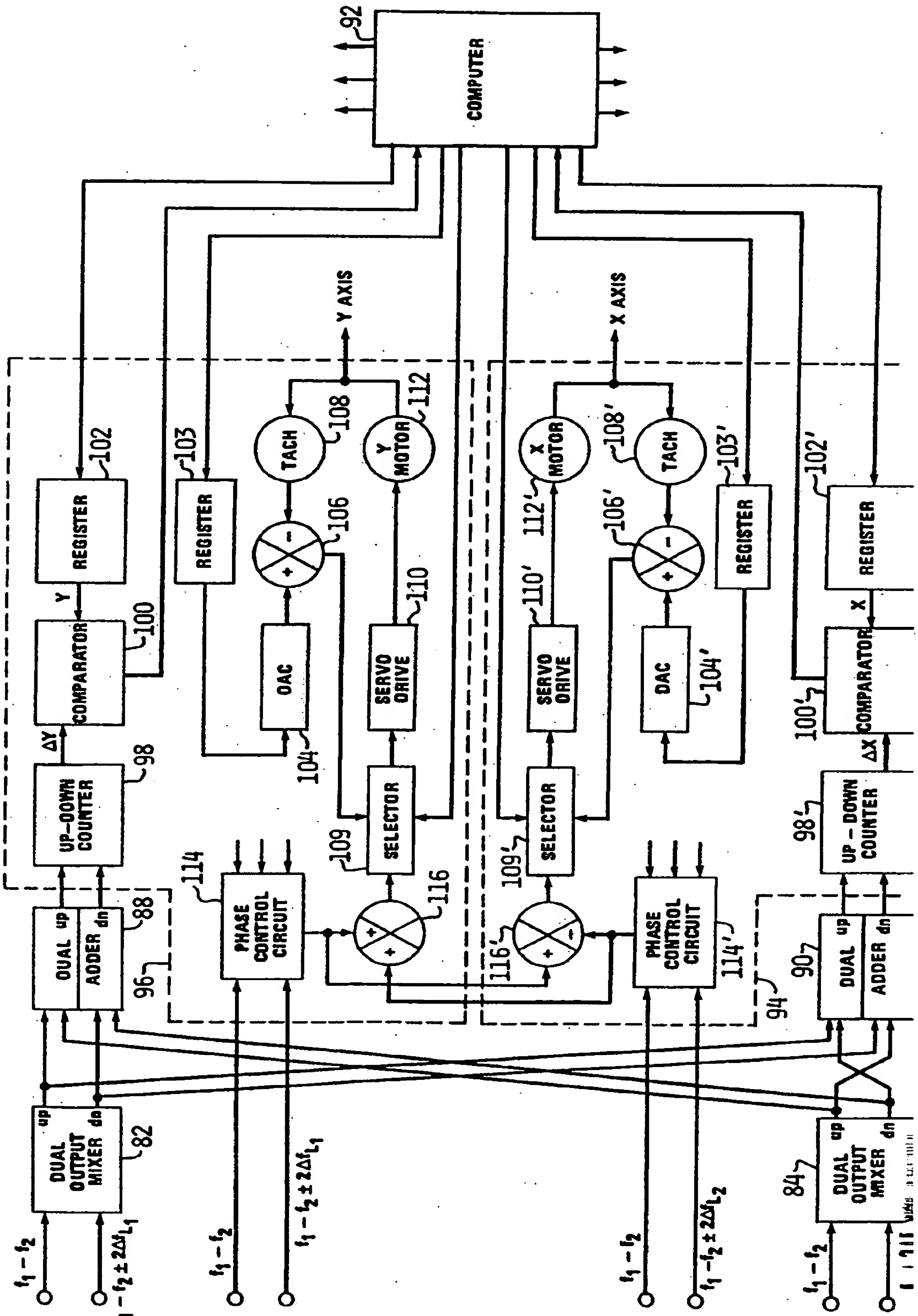
COMPUTER
92
Y AXIS
X AXIS
REGISTER
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103
103'
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TACH
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COMPARATOR
100
100'
Y
X
ΔY
ΔX
DAC
104
104'
SERVO DRIVE
SELECTOR
109
109'
UP-DOWN COUNTER
98
98'
PHASE CONTROL CIRCUIT
114
114'
116
116'
DUAL ADDER
up
dn
88
90
96
94
DUAL OUTPUT MIXER
82
84
$f_1 - f_2$
$f_1 - f_2 \pm 2\Delta f_{L_1}$
$f_1 - f_2 \pm 2\Delta f_{L_2}$

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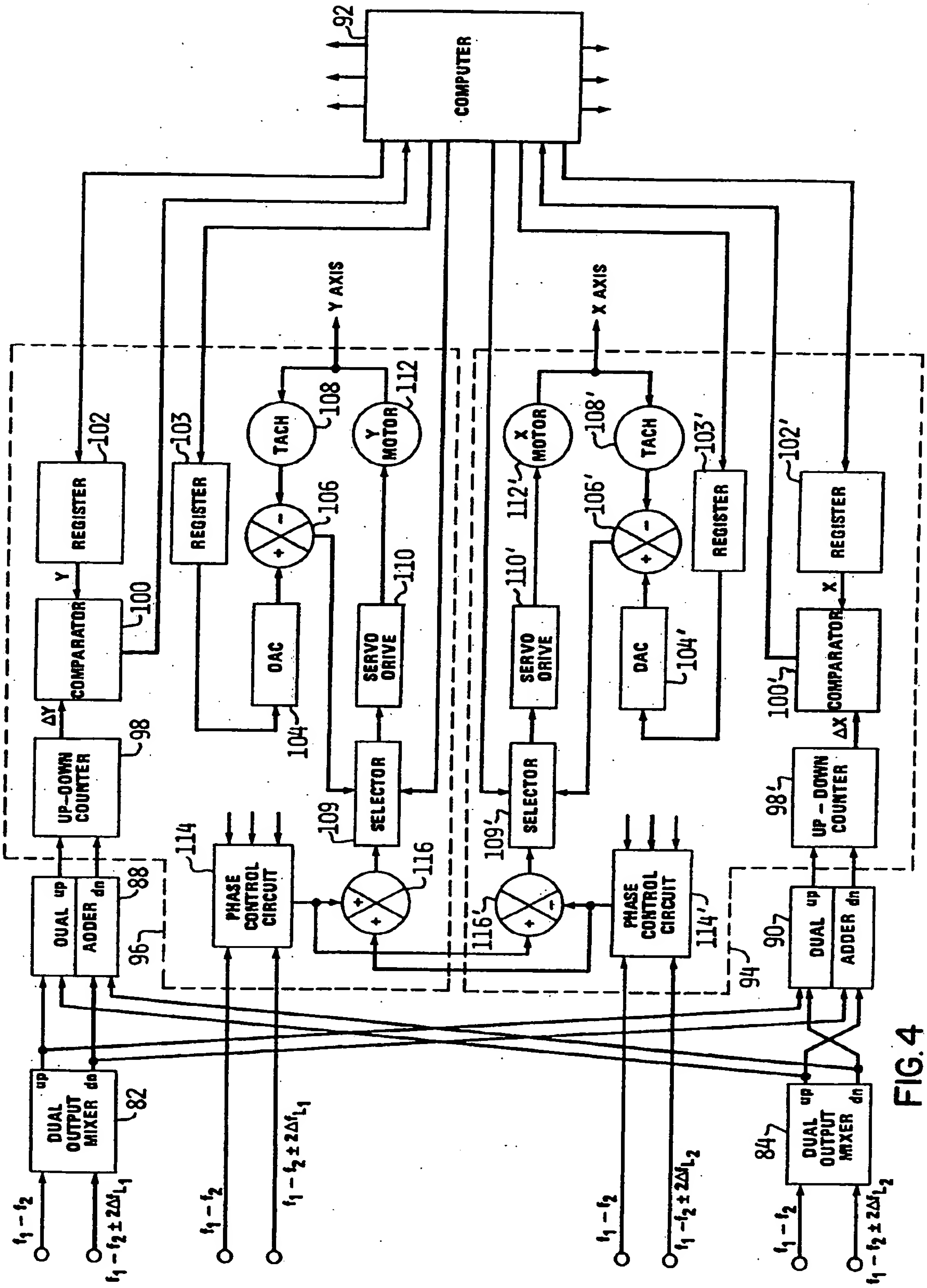

FIG. 4

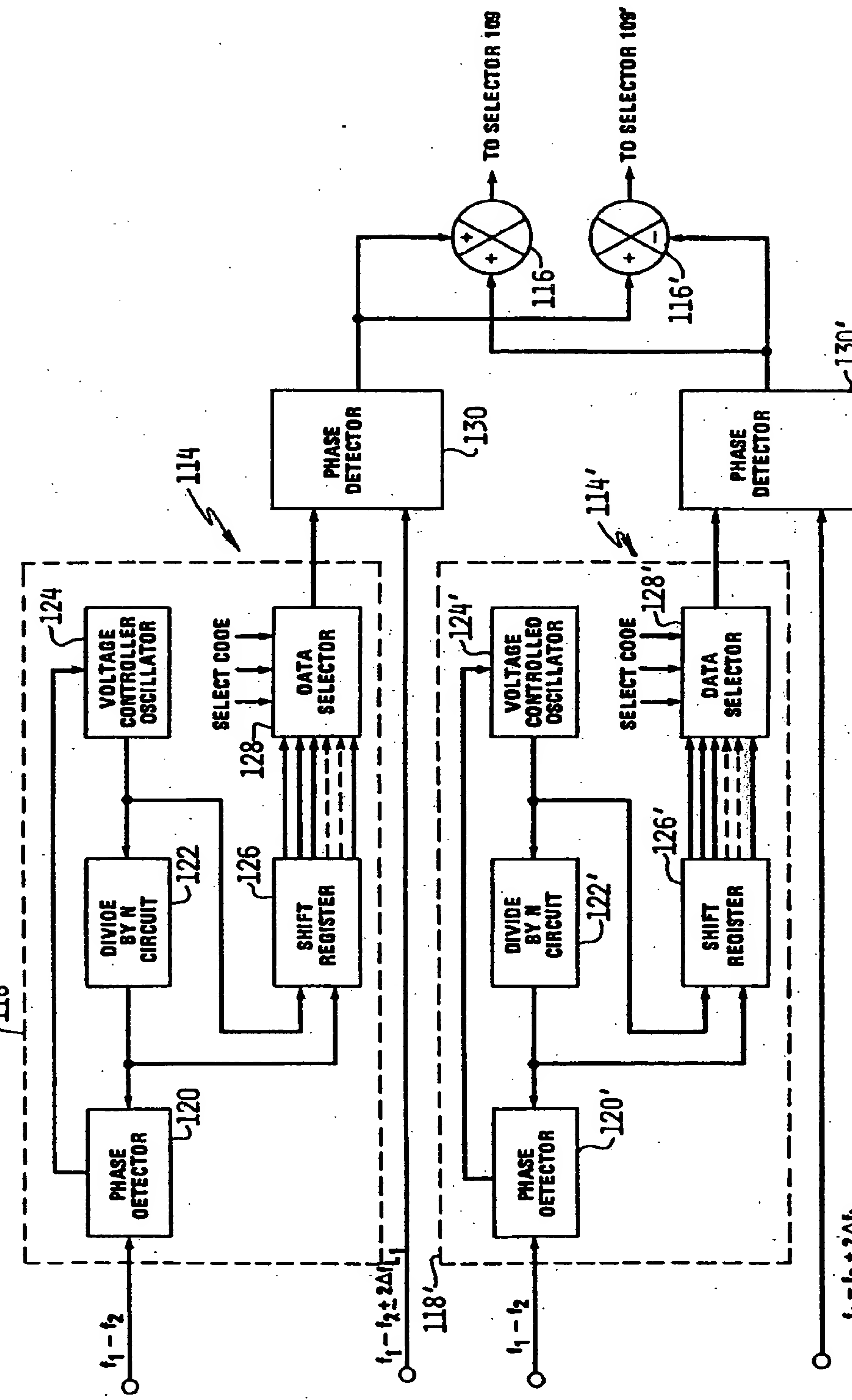
TO SELECTOR 109
TO SELECTOR 109'
116
116'
130
130'
PHASE DETECTOR
PHASE DETECTOR
114
114'
VOLTAGE CONTROLLED OSCILLATOR
VOLTAGE CONTROLLED OSCILLATOR
SELECT CODE
SELECT CODE
DATA SELECTOR
DATA SELECTOR
124
124'
128
128'
DIVIDE BY N CIRCUIT
DIVIDE BY N CIRCUIT
122
122'
126
126'
SHIFT REGISTER
SHIFT REGISTER
118
118'
120
120'
$f_1 - f_2$
$f_1 - f_2 \pm 2\Delta f_{L_1}$
$f_1 - f_2$
$f_1 - f_2 \pm 2\Delta f_{L_2}$

FIG.5

SPECIFICATION

Interferometrically controlled stage with precisely orthogonal axes of motion

This invention relates generally to interferometrically controlled stages movable along X and Y axes for positioning or aligning a first object, such as a photomask or a semiconductive wafer, with respect to a second object, such as a reticle, or an image thereof, and more specifically to an interferometrically controlled stage movable along precisely orthogonal X and Y axes for successively positioning or aligning different regions of a photomask or a semiconductive wafer with respect to the same reticle or an image thereof.

In the semiconductor industry interferometrically controlled stages movable along X and Y axes are employed both in the fabrication of photomasks and in the processing of semiconductive wafers to form integrated circuits and the like. A high (submicron) resolution photomask is typically fabricated by employing such an interferometrically controlled stage to successively position different regions of the photomask with respect to a reticle, or an image of a reticle, representing a level of microcircuitry to be printed on the photomask at each of those regions. This step-and-repeat printing operation forms an array of adjacent regions of microcircuitry of one level on the photomask in rows and columns parallel to the X and Y axes of motion of the interferometrically controlled stage. A set of such photomasks, each bearing an array of microcircuitry of a different level is typically employed in the fabrication of integrated circuits or the like from a semiconductive wafer. In the course of this fabrication, the semiconductive wafer is sequentially aligned with each photomask of the set and the level of microcircuitry printed on the photomask is in turn printed on the semiconductive wafer. However, it is also possible to eliminate the operation of forming a set of such photomasks by employing an interferometrically controlled stage to successively align different regions of the semiconductive wafer with each of the reticles employed in fabricating the set of photomasks so that the level of microcircuitry represented by each of those reticles may be printed directly on the semiconductive wafer at each of those regions during separate step-and-repeat printing operations.

In order to facilitate the precise positioning or alignment of an array of adjacent regions of one level of microcircuitry being printed on a photomask, or on a semiconductive wafer, relative to each array of adjacent regions of microcircuitry of another level previously printed or yet to be printed on the other photomasks of the same set, or relative to each array of adjacent regions of microcircuitry of another level previously printed or yet to be printed on the semi-conductive wafer, it would be highly desirable to employ an interferometerically controlled stage having precisely orthogonal X and Y axes of motion for step-and-repeat printing operations such as those described above. Unfortunately, however, conventional interferometrically controlled stages do not have precisely orthogonal X and Y axes of motion. Moreover, the degree of nonorthogonality of the X and Y axes of motion of such stages is normally different from stage to stage so that different stages have different frames of reference and cannot therefore be employed interchangeably in printing different levels of microcircuitry on different photomasks of the same set or on the same semiconductive wafer or batch of semiconductive wafers.

Conventional interferometrically controlled stages typically employ a separate inerferometer system for each axis of motion of the stage with a first movable mirror of the interferometer system for the X axis of motion being mounted on the stage in a vertical plane normal to the X axis of motion and with a second movable mirror for the Y axis of motion being mounted on the stage in a vertical plane normal to the Y axis of motion, as shown in British Patent No. 1,196,281 entitled INTERFEROMETRICALLY CONTROLLED POSITIONING APPARATUS.

Since these mirrors must be disposed in vertical planes precisely orthogonal to one another for the stage to have precisely orthogonal X and Y axes of motion, special measurement equipment and procedures involving considerable effort and expense are employed to mount and maintain these mirrors in vertical planes as closely orthogonal to one another as possible. However, since even the best measurement equipment has a finite accuracy, it is in fact not possible to mount and maintain these mirrors in precisely orthogonal vertical planes. As a result the stage does not have precisely orthogonal X and Y axes of motion.

Accordingly, it is the principal object of this invention to provide an interferometrically controlled stage having precisely orthogonal X and Y axes of motion.

Another object of this invention is to provide such a stage while eliminating the effort and expense in attempting to mount the first and second movable mirrors in precisely orthogonal vertical planes.

Still another object of this invention is to provide such a stage which may be employed interchangeably with other such stages in printing different levels of microcircuitry on different photomasks of the same set or on the same semiconductive wafer or batch of semiconductive wafers.

These and other objects are accomplished according to the illustrated preferred embodiment of this invention by employing a stage movable along X and Y axes in a horizontal plane, and by fixedly mounting first and second movable plane mirrors of first and second interferometer systems, respectively, on the stage in vertical planes intersecting one another at the Y axis with the first and second movable mirrors symmetrically disposed about the Y axis. First and second stationary plane mirrors are fixedly mounted above the stage on a housing of a projection lens or some other such utilization device and are disposed parallel to the first and second movable mirrors, respectively. The first interferometer system has a first measurement path normal to the first movable mirror and a first reference path normal to the first stationary mirror. As the stage is moved along either the X or the Y axis, the first

interferometer system produces a first measurement signal indicative of the veolcity of the first movable mirror while it is being moved (relative to the first stationary mirror) along the first measurement path. Similarly, the second interferometer system has a second measurement path normal to the second movable mirror and a second reference path normal to the second stationary mirror. As the stage is moved along either the X or the Y axis, the second interferometer system produces a second measurement signal indicative of the velocity of the second movable mirror while it is being moved (relative to the second stationary mirror) along the second measurement path. In response to sums and differences of these first and second measurement signals, first and second position control circuits move the stage along precisely orthogonal X and Y axes with the Y axis bisecting the angle between the first and second movable mirrors. Thus, the stage is provided with precisely orthogonal X and Y axes of motion without requiring the first and second movable mirrors to be mounted in precisely orthogonal vertical planes and without requiring any other such unattainable relationship between those mirrors or other parts of the stage. This eliminates the principal source of degradation in the orthogonality of the X and Y axes of motion of the stage. By comparison, other sources of degradation, such as unevenness of the first and second movable mirrors, are insignificant and are therefore disregarded for purposes of this application.

A further aspect of this invention relates generally to control circuits and more particularly to a position control circuit utilizing a phase-locked loop to extend the resolution of the position control circuit. Such position control circuits may be employed, for example, to control the position of an interferometrically controlled stage as described herein.

Conventional position control circuits for controlling the position of an interferometrically controlled stage typically employ a reversible or up-down counter to provide an indication of the actual position of the stage as described in U.S. Patent No. 3,458,259 entitled INTERFEROMETRIC SYSTEM and issued on July 28, 1969. The resolution of such position control circuits is therefore typically limited by the ambiguity of the last or least significant digit indicated by the counter.

Accordingly, it is an object of this further aspect of the present invention to provide an improved position control circuit in which the ambiguity of the last or least significant digit indicated by the counter is eliminated and the resolution of the position control circuit is extended.

This object is accomplished according to the illustrated preferred embodiment of this further aspect of the present invention by employing a position control circuit having a variable phase shifter responsive to an input reference signal and to a control signal for producing an output signal of the same frequency as the reference signal but shifted in phase as determined by the control signal, and by employing a phase detector responsive to the output signal from the variable phase shifter and to an input measurement signal of a frequency related to the frequency of the input reference signal for producing a position control signal extending the resolution of the position control circuit. The variable phase shifter comprises another phase detector responsive to the input reference signal and to an output signal from a divide by N circuit for driving a voltage controlled oscillator to supply the divide by N circuit with an output signal having a frequency N times greater than the frequency of the reference signal. A shift register is responsive to the output signals from both the voltage controlled oscillator and the divide by N circuit for supplying N output signals of different phase to a data selector. The data selector is responsive to the control signal for supplying a selected one of these N output signals to the first-mentioned phase detector as determined by the control signal.

There now follows a detailed description which is to be read with reference to the accompanying drawings of an interfermetrically controlled stage and of two position control circuits therefor according to the invention; it is to be clearly understood that this stage and the two circuits have been selected for description to illustrate the invention by way of example and not by way of limitation.

In the accompanying drawings:-

Figure 1 is a perspective rear view of an interferometrically controlled stage having precisely orthogonal X and Y axes of motion in accordance with the preferred embodiment of the present invention;

Figure 2 is a detailed schematic representation of one of the interferometer systems employed with the stage of Figure 1;

Figure 3 is a detailed block diagram of a pair of position control circuits employed for driving the stage of Figure 1;

Figure 4 is a detailed block diagram of another pair of position control circuits constructed in accordance with the preferred embodiment of the aforementioned further aspect of the present invention and employed, for example, in place of the position control circuits of Figure 3 to drive the interferometrically controlled stage of Figure 1; and

Figure 5 is a detailed block diagram of a pair of phase control circuits constructed in accordance with the preferred embodiment of this further aspect of the present invention and employed in the position control circuits of Figure 4.

Referring now to Figure 1, there is shown an interferometrically controlled stage 10 for use in aligning a workpiece such as a semiconductive wafer 12 with an object such as a reticle 14 or a projected image of the reticle. The stage 10 comprises a lower platform 16 supported by air bearings on the flat upper surface of a granite block 18 for movement generally along an X axis of the stage, and an upper platform 20 supported by air bearings on the flat upper surface of the granite block 18 (through clearance openings in the lower platform 16) for movement generally along an orthogonal Y axis of the stage. In addition, the upper platform 20 is coupled to the lower platform 16 for movement therewith generally along the X axis of the stage 10. Thus, the upper platform 20 of the stage 10 may be moved in a horizontal plane generally along the

orthogonal X and Y axes of the stage and, since such movements may occur simultaneously, may be moved along any straight line in that horizontal plane.

The semiconductive wafer 12 is held by a vacuum chuck 22 mounted on the upper platform 20 for movement therewith. Chuck 22 is positioned beneath a projection lens 26 or some other such utilization device for use in processing the semiconductive wafer 12. The reticle 14 is held by a vacuum holder 28 positioned directly above the projection lens 26 and along an optical axis 24 thereof. Both the projection lens 26 and the holder 28 for the reticle 14 are mounted on a frame attached to the granite block 18. In the process of fabricating integrated circuits or the like from the semiconductive wafer 12, the stage 10 is moved along the X and Y axes to successively align adjacent regions of one level of microcircuitry that may have already been formed on the semiconductive wafer with an image of another level of microcircuitry contained on the reticle 14 and yet to be printed on the semiconductive wafer at each of those regions. This image is projected onto the semiconductive wafer 12 by the projection lens 26.

In order to provide the stage 10 with precisely orthogonal X and Y axes of motion, two elongated plane mirrors 30 and 32 are fixedly mounted on the upper platform 20 for movement therewith. These mirrors (hereinafter being referred to as the first and second movable mirrors 30 and 32) are disposed symmetrically about the Y axis in respective first and second vertical planes intersecting one another at the Y axis at an angle of 2θ. No special measurement equipment or critical measurement procedures are required in mounting the first and second movable mirrors 30 and 32 on the upper platform 20 of the stage 10 since, as hereinafter described, the stage is controlled so that the X and Y axes are precisely orthogonal to one another with the Y axis bisecting the angle 2θ between the first and second movable mirrors. The first and second movable mirrors 30 and 32 may therefore be mounted in respective first and second vertical planes intersecting one another at virtually any angle, and, for purposes of illustration, are shown as being fixedly mounted on the upper platform 20 of the stage 10 at a nominal right angle to one another by a carrier 34. First and second plane mirrors 36 and 38 are fixedly mounted on a housing of the projection lens 26 above the carrier 34. These mirrors (hereinafter being referred to as the first and second stationary mirrors 36 and 38) correspond and are disposed parallel to the first and second movable mirrors 30 and 32, respectively.

First and second interferometer systems 40 and 42 are employed to precisely measure the velocities of the first and second movable mirrors 30 and 32 (relative to the first and second stationary mirrors 36 and 38) while they are being moved along corresponding first (or ΔL_1) and second (or ΔL_2) measurement paths normal to the first and second movable mirrors, respectively, as happens whenever the stage 10 is moved along either the X or the Y axis, and to produce measurement signals indicative of those velocities. Interferometer systems such as those manufactured and sold by Hewlett-Packard Company and described in detail in Hewlett-Packard Company's Application Note 197-2 for the 5501A laser transducer and the aforementioned U.S. Patent No. 3,458,259 may be employed as the first and second interferometer systems 40 and 42. The interferometer systems 40 and 42 share a two frequency single mode laser transducer 44, such as the Hewlett-Packard 5501A laser transducer, for emitting a beam of light 46 including a first component having frequency f_1 (hereinafter referred to as f_1 light) and a second parallel and overlapping component having a frequency f_2 (hereinafter referred to as f_2 light). These parallel and overlapping components of f_1 and f_2 light have linear horizontal and vertical polarizations (relative to the laser transducer 44), respectively. A beam bender 48 is employed to deflect the beam of light 46 from the laser transducer 44 upward to a beam splitter 50, which transmits fifty percent of the beam of light upward through an aperture 52 in a frame 54 for holding the block of granite 18. Beam splitter 50 also reflects fifty percent of the beam of light 46 from the laser transducer 44 to another beam bender 56 from which it is in turn deflected upward through an aperture 58 in frame 54.

The laser transducer 44, the beam benders 48 and 56, the beam splitter 50, and the various elements of the first and second interferometer systems 40 and 42 hereinafter described may all be mounted on a frame attached to the granite block 18 in the configuration shown. With the first and second movable mirrors 30 and 32 mounted on the carrier 34 at nominally forty-five degrees with respect to the Y axis as shown, the ΔL_1 and the ΔL_2 measurement paths of the first and second interferometer systems 40 and 42, respectively, are rotated nominally forty-five degrees with respect to the Y axis. Thus, with the laser transducer 44 mounted along the X axis as shown, the laser transducer must also be rotated nominally forty-five degrees with respect to the Y axis as shown to orient the polarizations of the f_1 light and the f_2 light at forty-five degrees with respect to the Y axis and hence parallel and orthogonal to each of the first and second interferometer systems 40 and 42. This is essential since maximum output signal is obtained from the first and second interferometer systems 40 and 42 when those polarizations are so oriented, whereas virtually no output signal can be obtained from the first and second interferometer systems when those polarizations are oriented at forty-five degrees with respect to each of the first and second interferometer systems.

Since the first and second interferometer systems 40 and 42 are identical, the same reference numbers are generally employed for the same elements of both interferometer systems (with the reference numbers for those of the second interferometer system being primed), and only the first interferometer system 40 is described in detail. Referring now also to Figure 2, the first interferometer system 40 includes a polarizing beam splitter 60 for reflecting f_1 light of linear horizontal polarization (represented by a double-headed arrow normal to the plane of the paper) passing through the aperture 52 of the frame 54 and for transmitting the f_2 light of linear vertical

polarization (represented by a double-headed arrow in the plane of the paper) passing through the aperture 52 (an auxiliary arrowhead in the plane of the paper is associated with each double-headed arrow to indicate the direction of propagation of the light). The f_1 light reflected by the polarizing beam splitter 60 passes forward through a quarter wave plate 62 to the first movable mirror 30 along a first portion 64 of the ΔL_1 measurement path which, as already described, is normal to the first movable mirror. As the upper platform 20 of the stage 10 is moved along either the X or the Y axis, the corresponding movement of the first movable mirror 30 (relative to the first stationary mirror 36) along the ΔL_1 measurement path causes the f_1 light to undergo a frequency change of $\pm\Delta f$ as it is reflected from the first movable mirror backward along the first portion 64 of the ΔL_1 measurement path and through the quarter wave plate 62. The quarter wave plate 62 converts the polarization of the f_1 light passing forward therethrough to right-hand circular polarization, which is in turn converted to left-hand circular polarization as the f_1 light is reflected from the first movable mirror 30, and converts the polarization of the $f_1\pm\Delta f$ light reflected backward therethrough to linear vertical polarization. Thus, the $f_1\pm\Delta f$ light is transmitted by the polarizing beam splitter 60 to an attached retroreflector 66 from which it is reflected forward through the polarizing beam splitter and quarter wave plate 62 to the first movable mirror 30 along a second portion 68 of the ΔL_1 measurement path. The $f_1\pm\Delta f$ light reflected from the first movable mirror 30 backward along the second portion 68 of the ΔL_1 measurement path undergoes another frequency change of $\pm\Delta f$ as the upper platform 20 of the stage 10 is moved along either the X or the Y axis. In this instance the quarter wave plate 62 converts the polarization of the $f_1\pm\Delta f$ light passing forward therethrough to left-hand circular polarization, which is in turn converted to right-hand circular polarization as the $f_1\pm\Delta f$ light is reflected from the first movable mirror 30, and converts the polarization of the $f_1\pm2\Delta f$ light reflected backward therethrough to linear horizontal polarization. The $f_1\pm2\Delta f$ light reflected backward along the second portion 68 of the ΔL_1 measurement path is therefore reflected by the polarizing beam splitter 60 downward through a mixing polarizer 70 to a photoelectric detector 72.

In a similar manner, the f_2 light transmitted by the polarizing splitter 60 passes forward through a quarter wave plate 74 to a beam bender 76 from which it is reflected to the first stationary mirror 36 along a portion 78 of a ΔL_1 reference path which, as already described above, is normal to the first stationary mirror (at least from the beam bender 76 forward). This f_2 light is reflected from the first stationary mirror 36 backward along the first portion 78 of the ΔL_1 reference path to the beam bender 76 and then through the quarter wave plate 74. The quarter wave plate 74 converts the polarization of the f_2 light passing forward therethrough along the first portion 78 of the ΔL_1 reference path to left-hand circular polarization, which is in turn converted to right-hand circular polarization as the f_2 light is reflected from the first stationary mirror 36, and converts the polarization of the f_2 light reflected backward therethrough along the first portion 78 of the ΔL_1 reference path to linear horizontal polarization. Thus the f_2 light reflected backward from the first stationary mirror 36 along the first portion 78 of the ΔL_1 reference path is reflected by the polarizing beam splitter 60 to the retroreflector 66 from which it is reflected back to the polarizing beam splitter where it is reflected through the quarter wave plate 74 and deflected by the beam bender 76 to the first stationary mirror along a second portion 80 of the ΔL_1 reference path. This f_2 light is reflected again from the first stationary mirror 36 backward along the second portion 80 of the ΔL_1 reference path to the beam bender 76 and then through the quarter wave plate 74. The quarter wave plate 74 converts the polarization of the f_2 light passing forward therethrough along the second portion 80 of the ΔL_1 reference path to right-hand circular polarization, which is in turn converted to left-hand circular polarization as the f_2 light is reflected again from the first stationary mirror 36, and converts the polarization of the f_2 light reflected backward therethrough along the second portion 80 of the ΔL_1 reference path to linear vertical polarization. The f_2 light reflected backward along the second portion 80 of the ΔL_1 reference path is therefore transmitted by the polarizing beam splitter 60 downward through the mixing polarizer 70 to the photoelectric detector 72 with the parallel and overlapping $f_1\pm2\Delta f$ light from the second portion 68 of the ΔL_1 measurement path in an output beam of light 73. For simplicity of illustration the paths of the input light beam 46 entering the polarizing beam splitter 60 and the output light beam 73 entering the photoelectric detector 72, the first and second portions 64 and 68 of the ΔL_1 measurement path, the first and second portions 78 and 80 of the ΔL_1 reference path, and the retroreflector 66 have been represented as being spatially disposed in the plane of the paper in Figure 2, whereas they are actually spatially disposed in a plane normal to the plane of the paper as shown in the perspective view of Figure 1.

The mixing polarizer 70 mixes the $f_1\pm2\Delta f$ light and the parallel and overlapping f_2 light of the output light beam 73 passing therethrough to provide each of those components of the output light beam entering the photoelectric detector 72 with a component of similar polarization. These similarly polarized components are mixed by the photoelectric detector 72 to produce a first electrical measurement signal having a frequency $f_1-f_2\pm2\Delta f_{L_1}$ at the output of the photoelectric detector. A second electrical measurement signal having a frequency $f_1-f_2\pm2\Delta f_{L_2}$ is produced in the same manner as described above by the second interferometer system 42 at the output of the photoelectric detector 72' of that system.

Referring now also to Figure 3, the first electrical measurement signal of frequency $f_1-f_2\pm2\Delta f_{L_1}$ is applied to a first input of a first dual output mixer 82 of the first interferometer system 40, and the second electrical measurement signal of frequency $f_1-f_2\pm2\Delta f_{L_2}$ is applied to a first input of a second dual output mixer 84 of the second interferometer

system 42. An electrical reference signal of frequency f_1-f_2 produced by the laser transducer 44 at an electrical output 86 thereof (see Figure 1) is applied to a second input of the first dual output mixer 82 and to a second input of the second dual output mixer 84. The first dual output mixer 82 combines the first measurement signal and the reference signal to produce a first pulse train measurement signal (hereinafter simply referred to in this description as the first pulse train signal) having a repetition rate of $2\Delta f_{L_1}$ on an up or a down output thereof as determined by whether the sign of the $\pm 2\Delta f_{L_1}$ component of the frequency of the first measurement signal is positive or negative, respectively. The repetition rate of this first pulse train signal is porportional to the velocity of the first movable mirror 30 while it is being moved (relative to the first stationary mirror 36) along the ΔL_1 measurement path of the first interferometer system 40, as happens whenever the upper platform 20 of the stage 10 is moved along either the X or the Y axis of motion of the stage. Similarly, the second dual output mixer 84 combines the second measurement signal and the reference signal to produce a second pulse train measurement signal (hereinafter simply referred to in this description as the second pulse train signal) having a repetition rate of $2\Delta f_{L_2}$ on an up or a down output thereof as determined by whether the sign of the $\pm 2\Delta f_{L_2}$ component of the frequency of the second measurement signal is positive or negative, respectively. The repetition rate of this second pulse train signal is proportional to the velocity of the second movable mirror 32 while it is being moved (relative to the second stationary mirror 38) along the ΔL_2 measurement path of the second interferometer system 42, as also happens whenever the upper platform 20 of the stage 10 is moved along either the X or the Y axis of motion of the stage.

Pulses of the first and second pulse train signals appearing on the up outputs of the first and second dual output mixers 82 and 84 are applied to a first pair of inputs of a first dual adder 88, which produces a pulse train representing the sum of those pulses on an up output of the first dual adder. Similarly, pulses of the first and second pulse train signals appearing on the down outputs of the first and second dual output mixers 82 and 84 are applied to a second pair of inputs of the first dual adder 88, which produces a pulse train representing the sum of those pulses on a down output of the first dual adder. The trains of pulses thereby produced on the up and down outputs of the first dual adder 88 represent the sum of the first and second pulse train signals. Pulses of the first pulse train signal appearing on the up output of the first dual output mixer 82 and pulses of the second pulse train signal appearing on the down output of the second dual output mixer 84 are applied to a first pair of inputs of a second dual adder 90, which produces the sum of those pulses on an up output of the second dual adder. Similarly, pulses of the first pulse train signal appearing on the down output of the first dual output mixer 82 and pulses of the second pulse train signal appearing on the up output of the second dual output mixer 84 are applied to a second pair of inputs of the second dual adder 90. The sums of pulses thereby produced on the up and down outputs of the second dual adder 90 represent the difference of the first and second pulse train signals.

In response to the difference and the sum of the first and second pulse train signals and to X and Y digital end point data signals received, for example, from a computer 92, X and Y axis position control circuits 94 and 96 move the upper platform 20 of the stage 10 along precisely orthogonal X and Y axes (with the Y axis bisecting the angle 2θ between the first and second movable mirrors 30 and 32) to precisely position the upper platform 20 as specified by the X and Y digital end point data signals. These movements of the upper platform 20 along precisely orthogonal X and Y axes are effected by the X and Y axes position control circuits 94 and 96 in accordance with the following equations as hereinafter explained:

(1) $\Delta X = K_x(\Delta L_1 - \Delta L_2)$, where $K_x = 1/2 \cos\theta$; and
(2) $\Delta Y = K_y(\Delta L_1 + \Delta L_2)$, where $K_y = 1/2 \sin\theta$.

The orthogonality of the ΔX and ΔY movements of the upper platform 20 along the X and Y axes of motion of the stage 10 in accordance with equations (1) and (2) is substantiated by the fact that ΔX is a function of cosine θ, whereas ΔY is a function of sine θ, and by the fact that such cosine and sine terms always exist in quadrature.

Since the X and Y axes position control circuits 94 and 96 are identical, the same reference numbers are employed for the same elements of both position control circuits (with those of the X axis position circuit being primed), and only the Y axis position control circuit is described in detail. Pulses appearing on the up and down outputs of the first adder 88 are applied to an up-down counter 98 for counting those pulses to produce a ΔY digital output signal proportional to the sum $(\Delta L_1 + \Delta L_2)$ of the displacements ΔL_1 and ΔL_2 of the first and second movable mirors 30 and 32 (relative to the first and second stationary mirrors 36 and 38) along the ΔL_1 and ΔL_2 measurement paths of the first and second interferometer systems 40 and 42, respectively, as the upper platform 20 of the stage 10 is moved along either the X or the Y axis of the stage. In effect, the up-down counter 98 integrates the sum of the velocities of the first and second movable mirrors 30 and 32 with respect to time as those velocities are measured by the first and second interferometer systems 40 and 42, respectively, to produce the ΔY digital output signal. This ΔY digital output signal is applied to one input of a comparator 100, and the Y digital end point data signal from the computer 92 is stored in a register 102 and applied to the other input of the comparator. The comparator 100 produces a digital comparison signal equal to the difference between the digital signals applied thereto and proportional to the distance the upper platform 20 must be moved along the Y axis to reach the Y axis position specified by the Y digital end point data signal. This digital comparison signal is applied to a digital-to-analog converter 104 which converts it to an analog voltage signal and applies it to one input of a summing circuit 106. Another analog voltage signal produced by a tachometer 108, as hereinafter explained, is

applied to the other input of the summing circuit 106. Thus, the summing circuit 106 produces an output voltage signal equal to the difference between the analog voltage signal from the analog-to-digital converter 104 and the tachometer 108. This output voltage signal is applied to a servo drive circuit 110 for driving a Y axis servo motor 112 mounted on the upper platform 20 and reacting against the lower platform 16 to move the upper platform along the Y axis to the Y axis position specified by the Y digital end point data signal. The tachometer 108 is coupled to the Y axis servo motor 112 for producing an analog voltage signal proportional to the speed of the Y axis servo motor and applying it to the summing circuit 106. This reduces the output voltage signal from the summing circuit 106 and therefore slows the Y axis servo motor 112 down as the upper platform 20 approaches the Y axis position specified by the Y digital end point data signal so as to impede the upper platform from overshooting the specified Y axis position.

The up-down counter 98' of the X-axis position control circuit 94 similarly integrates the difference of the velocities of the first and second movable mirrors 30 and 32, and those velocities are measured by the first and second interferometer systems 40 and 42, respectively, to produce a ΔX digital output signal proportional to the difference $(\Delta L_1-\Delta L_2)$ of the displacements ΔL_1 and ΔL_2 of the first and second movable mirrors (relative to the first and second stationary mirrors 36 and 38) along the ΔL_1 and ΔL_2 measurement paths of the first and second interferometer systems, respectively, while the upper platform 20 of the stage 10 is moved along either the X or the Y axis of the stage. In response to this ΔX digital output signal and an X digital end point data signal stored in the register 102' by the computer 92, the servo drive circuit 110' drives the X axis servo motor 112', which is mounted on the lower platform 16 of the stage 10 and which reacts against the granite block 18, to move the lower platform 16 and, hence, the upper platform 20 to the X axis position specified by the X digital end point data signal.

Thus, it may be seen that the upper platform 20 is moved along precisely orthogonal X and Y axes in accordance with the difference $(\Delta L_1-\Delta L_2)$ and the sum $(\Delta L_1+\Delta L_2)$ of the displacements of the first and second movable mirrors 30 and 32 (relative to the first and second stationary mirrors 36 and 38) along the ΔL_1 and ΔL_2 measurement paths of the first and second interferometer systems 40 and 42, respectively, as specified by the corresponding terms of equations (1) and (2) above. In actuality the constants K_x and K_y of those equations may be determined without the necessity of precisely measuring or knowing the half angle θ between the first and second movable mirrors 30 and 32. These constants can be determined in setting up the stage 10 by simply attaching a reference contact member to the upper platform 20; placing a gage block of, for example, four inches in length on the upper platform along the Y axis and in abutment with the reference contact member; mounting a deflection type sensor of an electronic gage at a fixed position (with respect to the upper platform) along the Y axis and in the path of the gage block and the reference contact member; moving the stage forward along the Y axis to bias the gage block against the sensor until the electronic gage is zeroed and then also zeroing the up-down counter 98 of the Y axis position sensor 96; moving the upper platform backward along the Y axis and removing the gage block; moving the upper platform forward along the Y axis again to bias the reference contact member against the sensor until the electronic gage is zeroed again; dividing the length of the gage block by the counter thereupon registered in the up-down counter 98 to determine K_y in inches per count; and by repeating the same process for the X axis with the same reference contact member, the same gage block, and the up-down counter 98' of the X axis position control circuit 94 to determine K_x in inches per count. Since gage blocks are commonly calibrated by the National Bureau of Standards to submicroinch accuracies, this set up procedure permits the upper platform 20 of the stage 10 to be moved along the orthogonal X and Y axes with extremely high precision. The constants K_x and K_y, along with other constants such as might be employed to compensate for changes in atmospheric conditions etc., are stored in the computer 92 and utilized in determining a set of pairs of X and Y end point data signals required for a desired step-and-repeat operation. As each pair of X and Y end point data signals is fed by the computer 92 to the registers 102' and 102 of the X and Y axis position control circuit 94 and 96, the upper platform 20 of the stage 10 is successively stepped along precisely orthogonal X and Y axes to the position specified by that pair of X and Y end point data signals so as to successively align adjacent regions of microcircuitry of one level on the semiconductive wafer 12 with the projected image of the reticle 14. Since the upper platform 20 is stepped along precisely orthogonal X and Y axes, other such stages may therefore be employed interchangeably in printing different levels of microcircuitry on the same semiconductive wafer 12.

Referring now to Figure 4, there is shown another pair of X and Y axes position control circuits 96 and 94 that may be employed in place of those described above in connection with Figure 3 to control the position of the interferometrically controlled stage of Figure 1. Since these X and Y axes position control circuits 96 and 94 are identical, the same reference numbers are again employed for the same elements of both position control circuits (with those of the X axis position control circuit being primed), and only the Y axis position control circuit 96 is described in detail. Pulses appearing on the up and down outputs of the first dual adder 88 are again applied to an up-down counter 98 for counting those pulses to produce a ΔY digital output signal proportional to the sum $(\Delta L_1+\Delta L_2)$ of the displacements ΔL_1 and ΔL_2 of the first and second movable mirrors 30 and 32 (relative to the first and second stationary mirrors 36 and 38) along the ΔL_1 and ΔL_2 measurement paths of the first and second interferometer systems 40 and 42, respectively as the upper platform 20 of the stage 10 is moved along either the X or the Y

axis. In effect, the up-down counter 98 again integrates the sum of the velocities of the first and second movable mirrors 30 and 32 with respect to time as those velocities are measured by the first and second interferometer systems 40 and 42, respectively, to produce the ΔY digital output signal. This ΔY digital output signal is again applied to one input of a comparator 100, and the Y digital end point data signal from the computer 92 is again stored in a register 102 and applied to the other input of the comparator. The comparator 100 again produces a digital comparison signal equal to the difference between the digital signals applied thereto and proportional to the distance the upper platform 20 of the stage 10 must be moved along the Y axis to reach the Y axis position specified by the Y digital end point data signal. This digital comparison signal is applied to the computer 92, which in response to a nonzero comparison signal sequentially stores each of a series of digital velocity signals in a register 103. These digital velocity signals and the durations they are stored in register 103 define an optimum profile of accelerating, maximum, and decelerating velocities, as determined in accordance with well known techniques, for the distance the upper platform 20 of the stage 10 is to be moved along the Y axis. Each digital velocity signal stored in the register 103 is applied to a digital-to-analog converter 104 which converts it to an analog voltage signal and applies it to one input of a summing circuit 106. Another analog voltage signal produced by a tachometer 108, as hereinafter explained, is applied to the other input of the summing circuit 106. Thus, the summing circuit 106 produces an output voltage signal equal to the difference between the analog voltage signal from the analog-to-digital converter 104 and the tachometer 108. In response to a nonzero comparison signal from the comparator 100, the computer 92 also activates a selector circuit 109 to apply the output voltage signal from the summing circuit 106 to a servo drive circuit 110 for driving a Y axis servo motor 112. This Y axis servo motor is mounted on the upper platform 20 and reacts against the lower platform 16 of the stage 10 to move the upper platform along the Y axis towards the Y axis position specified by the Y digital end point data signal. The tachometer 108 is coupled to the Y axis servo motor 112 for producing an analog voltage signal proportional to the actual velocity of the Y axis servo motor and applying it to the summing circuit 106. This reduces the output voltage signal from the summing circuit 106 for the purpose of equalizing the actual velocity and the desired velocity of the Y axis servo motor 112.

The up-down counter 98' of the X-axis position control circuit 94 similarly integrates the difference of the velocities of the first and second movable mirrors 30 and 32 as those velocities are measured by the first and second interferometer systems 40 and 42, respectively, to produce a ΔX digital output signal proportional to the difference $(\Delta L_1-\Delta L_2)$ of the displacements ΔL_1 and ΔL_2 of the first and second movable mirrors (relative to the first and second stationary mirrors 36 and 38) along the ΔL_1 and ΔL_2 measurement paths of the first and second interferometer systems, respectively, while the upper platform 20 of the stage 10 is moved along either the X or the Y axis of the stage. In response to this ΔX digital output signal and an X digital end point data signal stored in the register 102' by the computer 92, the servo drive circuit 110' drives the X axis servo motor 112'. This X axis servo motor is mounted on the lower platform 16 of the stage and reacts against the granite block 18, on which both the upper and lower platforms 20 and 16 are mounted, to move the lower platform and, hence, the upper platform, which is coupled to the lower platform for movement therewith along the X axis, towards the X axis position specified by the X digital end point data signal.

Thus, it may be seen that the upper platform 20 is again moved along the orthogonal X and Y axes in accordance with the difference $(\Delta L_1-\Delta L_2)$ and the sum $(\Delta L_1+\Delta L_2)$ of the displacements of the first and second movable mirrors 30 and 32 (relative to the first and second stationary mirrors 36 and 38) along the ΔL_1 and ΔL_2 measurement paths of the first and second interferometer systems 40 and 42, respectively, as specified by the corresponding terms of equations (1) and (2) above. In actuality the constants K_x and K_y of those equations may be determined without the necessity of precisely measuring or knowing the half angle θ between the first and second movable mirrors 30 and 32 as described above. The constants K_x and K_y, along with other constants such as might be employed to compensate for changes in atmospheric conditions etc., are stored in the computer 92 and utilized in determining a set of pairs of X and Y end point data signals successively fed by the computer 92 to the registers 102' and 102 of the X and Y axes position control circuits 94 and 96, as described above, to successively step the upper platform 20 of the stage 10 along the orthogonal X and Y axes to the position specified by those pairs of X and Y end point data signals.

The resolution of the X and Y axes position control circuits 94 and 96 of Figure 4 is extended in accordance with the perferred embodiment of a further aspect of the present invention by providing the Y axis position control circuit 96 with a phase control circuit 114, responsive to the reference signal of frequency f_1-f_2, the first measurement signal of frequency $f_1-f_2\pm2\Delta f_{L_1}$, and a three bit control or select code signal supplied by the computer 92 in response to a zero comparison signal from the comparator 100, for producing a position control signal as hereinafter described. Similarly, the X axis position control circuit 94 is provided with a phase control circuit 114', responsive to the reference signal of frequency f_1-f_2, the second measurement signal of frequency $f_1-f_2\pm2\Delta f_{L_2}$, and another three bit control or select code signal supplied by the computer 92 in response to a zero comparison signal from the comparator 100', for producing another position conrol signal as hereinafter described. These position control signals are applied to a pair of inputs of a summing circuit 116 (in the Y axis position control circuit 96) for producing an output voltage signal equal to the sum of the position control signals. They are also applied to a pair of

inputs of a summing circuit 116' (in the X axis position control circuit 94) for producing an output voltage signal equal to the difference of the position control signals. In response to zero comparison signals from the comparators 100 and 100' the computer 92 activates the selector circuits 109 and 109' to apply the output voltage signals from the summing circuits 116 and 116' to the servo drive circuits 110 and 110', respectively. This drives and Y and X axes servo motors 112 and 112' to move the upper platform 20 of the stage 10 to precisely the desired Y and X axes positions.

Referring now to Figure 5, there is shown a detailed block diagram of the phase control circuits 114 and 114' for the Y and X axes position control circuits 96 and 94, respectively, of Figure 4. Since these phase control circuits 114 and 114' are identical, the same reference numbers are employed for the same elements of both phase control circuits (with those of the phase control circuit 114' for the X axis position control circuit 94 of Figure 4 being primed), and only the phase control circuit 114 for the Y axis position control circuit 96 of Figure 4 is described in detail.

The phase control circuit 114 includes a variable phase shifter 118 for receiving the reference signal of frequency f_1-f_2 and for producing an output signal of the same frequency but shifted in phase as determined by the three bit select code from the computer 92. This phase shifter comprises a phase detector 120 having a first input at which the reference signal of frequency f_1-f_2 is applied and a second input at which an output signal from a divide by N circuit 122 is applied as hereinafter explained. In response to these input signals the phase detector 120 applies an output voltage signal to a voltage controlled oscillator 124 so as to drive the voltage controlled oscillator to produce an output signal having a frequency N times greater than the frequency f_1-f_2 of the reference signal. This output signal from the voltage controlled oscillator 124 is applied both to an input of the divide by N circuit 122 and to a clock input of a shifter register 126. The divide by N circuit 122 divides this output signal by N, which for purposes of illustration is herein taken to have a value of eight, and applied the resultant output signal to the second input of the phase detector 120 and also to a date input of the shifter register 126. In response to the applied output signals from the divide by N circuit 122 and the voltage controlled oscillator 124, the shift register 126 supplies N (or eight) output signals of different phase (each such output signal differing in phase from the preceding one by 360°/N or 45°) to a data selector 128. The data selector 128 supplies a selected one of these output signals from the shift register 126 to the output of the variable phase shifter 118 as determined by the three bit select code signal supplied by the computer 92 in response to a zero comparison signal from the comparator 100. As indicated above, the selected output signal has the same frequency f_1-f_2 as the reference signal.

The phase control circuit 114 also includes a phase detector 130 having a first input at which the selected output signal (i.e., the output signal with the desired phase shift) of frequency f_1-f_2 from the variable phase shifter 118 is applied and a second input at which the first measurement signal of frequency $f_1-f_2\pm2\Delta f_{L_1}$ is applied. In response to these signals the phase detector 130 supplies a position control signal proportional to the difference in phase therebetween to an input of each of the summing circuits 116 and 116' as previously described. Similarly, the variable phase shifter 118' and the phase detector 130' of the phase control circuit 114' are responsive to the reference signal of frequency f_1-f_2, to the other three bit select code signal from the computer 92, and to the second measurement signal of frequency $f_1-f_2\pm2\Delta f_{L_2}$ for supplying another position control signal proportional to the difference in phase between the selected output signal from the variable phase shifter 118' and the second measurement signal to the other input of each of the summing circuits 116 and 116'. The sum and difference of these position control signals are applied to the selector circuits 109 and 109' of the Y and X axes position control circuits 96 and 94, respectively, of Figure 4 to extend the resolution of those position control circuits as previously described.

CLAIMS

1. A stage movable along orthogonal first and second axes, said stage including a platform movable nominally along the first and second axes, first and second reference members mounted on the platform for movement therewith and nominally symmetrically disposed about the first axis in planes intersecting one another nominally at the first axis, first and second measurement means provided for producing first and second measurement signals indicative of the movement of the first and second reference members along first and second measurement paths nominally normal to the first and second reference members, respectively, while the platform is being moved along either the first or the second axis, and first and second control means responsive to the sum and the difference of the first and second measurement signals for constraining the platform to move along the orthogonal first and second axes.

2. An interferometrically controlled stage according to claim 1 wherein said platform is movable nominally along the first and second axes in a first plane, said first and second reference members comprise first and second movable mirrors nominally symmetrically disposed about the first axis in second and third planes nominally normal to the first plane and intersecting one another nominally at the first axis, said first and second measurement means comprise first and second interferometer systems for producing first and second measurement signals indicative of the movement of the first and second movable mirrors along the first and second measurement paths, respectively, while the platform is being moved along either the first or the second axis, and said first and second control means comprise first and second position control circuits responsive to the sum and the difference of the first and second measurement signals for moving the platform along the orthogonal first and second axes

from one position to another with the first axis bisecting the angle between the first and second movable mirrors.

3. An interferometrically controlled stage according to claim 2 wherein said first and second interferometer systems produce first and second measurement signals proportional to the velocities of the first and second movable mirrors along the first and second measurement paths, respectively, while the platform is being moved along either the first or the second axis of the stage, and said first and second position control circuits integrate the sum and the difference of the first and second measurement signals with respect to time to produce first and second actual position signals proportional to the sum and the difference, respectively, of the displacements of the first and second movable mirrors along the first and second measurement paths, respectively, and move the platform along the orthogonal first and second axes of the stage as determined by the differences between those first and second actual position signals and first and second desired position signals, respectively.

4. An interferometrically controlled stage according to either one of claims 2 and 3 wherein said stage includes a chuck mounted on the platform for movement therewith and for holding a workpiece to be successively stepped to different positions with respect to a utilization device and said first and second position control circuits are responsive to successive pairs of first and second desired position signals for successively stepping the platform to different positions along the orthogonal first and second axes to successively position different regions of the workpiece with respect to the utilization device.

5. An interferometrically controlled stage according to any one of claims 2, 3 and 4 wherein said stage includes a granite block, said platform comprises a first platform mounted for movement on the granite block nominally along the first axis, said stage includes a second platform mounted for movement on the granite block nominally along the second axis, said first platform being coupled to the second platform for movement therewith along the second axis, and said first and second position control circuits are coupled to the first and second platforms, respectively, for moving the first platform along the orthogonal first and second axes in response to the sum and the difference of the first and second measurement signals, respectively.

6. An interferometrically controlled stage according to claim 5 comprising first combining means responsive to the first and second measurement signals for applying a signal respresentative of the sum of those signals to the first position control circuit, and second combining means responsive to the first and second measurement signals for applying a signal respresentative of the difference of those signals to the second position control circuit.

7. An interferometrically controlled stage according to Claim 6 wherein said first position control circuit comprises first counter means, coupled to the first combining means, for integrating the sum of the first and second measurement signals with respect to time to produce a first actual position signal proportional to the sum of the displacements of the first and second movable mirrors along the first and second measurement paths respectively, first register means for receiving a first desired position signal, first comparator means, coupled to the first counter means and to the first register means, for producing a first comparison signal equal to the difference between the first actual and desired position signals, and first drive means coupled to the first comparator means and to the first platform, for moving the first platform along the first axis to a position designated by the first desired position signal, and said second position control circuit comprises second counter means coupled to the second combining means, for integrating the difference of the first and second measurement signals with respect to time to produce a second actual position signal proportional to the difference of the displacements of the first and second movable mirrors along the first and second measurement paths, respectively, second register means for receiving a second desired position signal, second comparator means, coupled to the second counter means and to the second register means, for producing a second comparison signal equal to the difference between the second actual and desired position signals, and second drive means coupled to the second comparator means and to the second platform, for moving the first platform along the second axis to a position designated by the second desired position signal.

8. An interferometrically controlled stage according to claim 7 wherein said first drive means comprises a first motor, coupled to the first platform, for moving the first platform along the first axis, a first summing circuit, responsive to the first comparator means and to a source of signal related to the speed of the first motor, for producing a signal related to the difference between a desired signal and the signal related to the speed of the first motor, and a first servo drive circuit coupled to the first summing circuit and to the first motor, for driving the first motor to move the first platform along the first axis to the position designated by the first desired position signal, and said second drive means comprises a second motor, coupled to the second platform, for moving the first platform along the second axis, a second summing circuit responsive to the second comparator means and to a source of signal related to the speed of the second motor, for producing a signal related to the difference between a desired signal and the signal related to the speed of the second motor, and a second servo drive circuit, coupled to the second summing circuit and to the second motor, for driving the second motor to move the first platform along the second axis to the position designated by the second desired position control signal.

9. An interferometrically controlled stage according to any one of claims 5, 6, 7 and 8 wherein said first platform is movable along the first and second axes of the stage in a horizontal plane, and said first and second movable mirrors are each mounted in a vertical plane.

10. An interferometrically controlled stage according to claim 9 wherein a holder is fixedly mounted with respect to the stage and disposed above the first platform for holding a reticle to be imaged onto the workpiece held by the chuck, and a projection lens is fixedly mounted with respect to the stage and disposed between the holder and the first platform for projecting an image of the reticle held by the holder onto the workpiece held by the chuck, and said first and second position control circuits are responsive to successive pairs of first and second desired position signals for successively stepping the first platform to different positions along the orthogonal first and second axes to successively position different regions of the workpiece with respect to the reticle in a stepping operation.

11. An interferometrically controlled stage according to either one of claims 9 and 10 wherein first and second stationary mirrors are fixedly mounted with respect to the first platform and disposed nominally parallel to the first and second movable mirrors, respectively, said first interferometer system includes first optical means for directing input light of a first frequency along the first measurement path to the first movable mirror, for directing input light of a second frequency along a reference path to the first stationary mirror, and for combining light reflected at least once from the first stationary mirror and light reflected at least once from the first movable mirror and shifted in frequency, as the first platform is moved along either the first or the second axis to provide a first output beam of light having a first component of the same frequency as the light reflected at least once from the first movable mirror and a second component of the same frequency as the light reflected at least once from the first stationary mirror, first photoelectric detector means for receiving the first output beam of light and for producing therefrom a first output signal having a frequency equal to the difference in frequency of the first and second components of the first output beam of light, and first mixing means, coupled to the first photoelectric detector means and to a source of signal having a frequency equal to the difference in frequency of the input light of the first frequency and the input of the second frequency, for producing the first measurement signal, and said second interferometer system includes second optical means for directing input light of a first frequency along the second measurement path to the second movable mirror, for directing input light of a second frequency along a second reference path to the second stationary mirror, and for combining light reflected at last once from the second stationary mirror and light reflected at least once from the second movable mirror and shifted in frequency, as the first platform is moved along either the first or the second axis to provide a second output beam of light having a first component of the same frequency as the light reflected at least once from the second movable mirror and a second component of the same frequency as the light reflected at least once from the second stationary mirror, second photoelectrical detector means for receiving the second output beam of light and for producing therefrom a second output signal having a frequency equal to the difference in frequency of the first and second components of the second output beam of light, and second mixing means, coupled to the second photoelectric detector means and to the source of signal having a frequency equal to the difference in frequency of the input light of the first frequency and the input light of the second frequency, for producing the second measurement signal.

12. An interferometrically controlled stage substantially as hereinbefore described with reference to the accompanying drawings.

13. A position control circuit comprising first means responsive to a reference signal and to a control signal (select code) for producing an output signal having the same frequency as the reference signal and having a phase determined by the control signal, and second means coupled to the first means and responsive to the output signal therefrom and to an input signal having a frequency related to the reference signal for producing a position control signal proportional to the difference in phase between the input signal and the output signal from the first means.

14. A position control circuit according to claim 13 wherein said first means comprises a variable phase shifter, and said second means comprises a phase detector.

15. A position control circuit according to claim 14 wherein said variable phase shifter comprises a voltage controlled oscillator for producing an output signal having a frequency N times greater than the frequency of the reference signal, a division circuit coupled to the voltage controlled oscillator for producing an output signal having a frequency equal to the frequency of the output signal therefrom divided by N, another phase detector coupled to the division circuit and to the voltage controlled oscillator and responsive to the output signal from the division circuit and to the reference signal for driving the voltage controlled oscillator to produce an output signal having a frequency N times greater than the frequency of the reference signal, a shift register coupled to the voltage controlled oscillator and to the last mentioned phase detector for producing N output signals of different phase, and a data selector coupled to the shift register and to the first-mentioned phase detector and responsive to the control signal (select code) for applying a selected one of the output signals from the shift register as determined by the control signal to the first-mentioned phase detector.

16. A position control circuit substantially as hereinbefore described with reference to Figure 3 of the accompanying drawings.

17. A position control circuit substantially as hereinbefore described with reference to Figure 4 of the accompanying drawings.

Printed for Her Majesty's Stationery Office by Croydon Printing Company Limited, Croydon Surrey, 1980.
Published by the Patent Office, 25 Southampton Buildings, London, WC2A 1AY, from which copies may be obtained.